LLNL-PROC-655360

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June 4, 2014

20th Topical Conference on High-Temperature Plasma Diagnostics
Atlanta, GA, United States
June 1, 2014 through June 5, 2014

Spectral content of buried Ag foils under long-pulse laser illumination

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Sources of 5-12 keV thermal He_α x-rays are readily generated by laser irradiation of mid-Z foils at intensities $> 10^{14}$ W/cm^2, and are widely used as probes for ICF and HED experiments. Higher energy 17-50 keV x-ray sources are efficiently produced from "cold" Kα emission using short pulse, petawatt lasers at intensities $> 10^{18}$ W/cm^2 [1, 2]. However, when long pulse (>1 ns) lasers are used with Z > 30 elements, the spectrum contains contributions from both K shell transitions and from ionized atomic states. Here we show that by sandwiching a silver foil between layers of high-density carbon (HDC), the ratio of Kα:He_α in the x-ray spectrum is significant increased over directly illuminated Ag foils, with narrower lines from K-shell transitions. Additionally, the emission volume is more localized for the sandwiched target, producing a more planar x-ray sheet. This technique may be useful for generating probes requiring spectral purity and spatial coherence, for example in incoherent x-ray Thomson scattering experiments.

I. INTRODUCTION

Bright, high-energy x-ray sources are essential in high-energy-density experiments, where they are used as diagnostic probes for x-ray radiography and incoherent x-ray Thomson scattering (TS) measurements. In TS experiments, the cross section for incoherent scattering increases with greater x-ray probe energy, while absorption falls (with the exception of edge transitions in the target of interest), making high energy sources desirable. In this application the scattered photon signal contains information about the target plasma. In particular, information about the electron velocity distribution (plasma temperature, T_e) is contained in the Compton shifted peak, which is Doppler broadened proportional to T_e. An accurate measurement of the plasma temperature requires an x-ray probe as narrowly peaked as possible; a source with broad "shoulders" around the characteristic x-ray lines obscures the T_e measurement. Additionally, a source with a small spatial extent – either a 2D point source or a 1D planar source – can be used to locally probe a specific region of a target in a TS experiment and is of obvious benefit when using point- or slit-projection radiography.

X-ray sources are commonly created in HED experiments by direct laser-irradiation of period four transition metals, which are readily ionized for laser intensity $>10^{14}$ W/cm^2. The resulting charge state distribution is strongly peaked at He-like, and the spectrum is dominated by He_α characteristic x-rays (from 4.3 keV for Sc to 9.0 keV from Zn) from the heated blow-off plasma. However, with increasing atomic number the efficiency of ionization decreases and transitions in Li-like, Be-like, and other lower charge state atoms are more pronounced. At higher laser intensities, x-rays are also generated by hot-electron refluxing in the un-heated material, generating K_α radiation. This mechanism of x-ray becomes more efficient (as measured by conversion efficiency of laser energy to x-ray energy) for laser intensities $> 10^{18}$ W/cm^2 [2].

II. EXPERIMENTAL DETAILS

The source of x-rays in these experiments were nominally identical, 300 μm × 300 μm × 10 μm-thick Ag foil ("μ-flags," see Ref. [1]). In one case, the foil was glued to a 100 μm-thick high-density carbon (HDC) layer on one side and a 10 μm-thick layer on the opposing side, creating a buried Ag layer. A second Ag target was tamped with 100 μm of HDC, while the third was free-standing Ag foil. Each was illuminated with by 18 beams from the OMEGA laser, which were focused to a spot size of ≈ 150 μm diameter and delivered a total of 9 kJ to the target face. The pulse was 1 ns square, yielding a total intensity of ≈ 5 × 10^{16} W/cm^2. Targets are shown with the laser-irradiated surface indicated in Fig. 1.

To measure the x-ray spectrum generated by each target, the transmission crystal spectrometer (TCS) viewed the targets face-on to the laser-illuminated surface [3]. The TCS spectral range of ∼ 16 - 70 keV recorded the Ag K-shell and ionized atomic emission lines (21 - 25 keV) as well as the higher energy background produced from each target. The signal was

* huntington4@llnl.gov; Contributed paper published as part of the Proceedings of the 20th Topical Conference on High-Temperature Plasma Diagnostics, Atlanta, Georgia, June, 2014

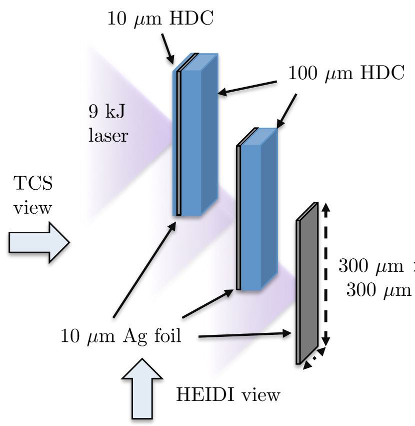

FIG. 1: Three target types fielded for this experiment: 10 μm of Ag sandwiched between 10 μm and 100 μm layers of HDC, 10 μm Ag backed by 100 μm HDC, and a stand-along 10 μm-thick Ag foil. Each was illuminated by the same laser pulse and interrogated by the TCS and HERIE diagnostics.

recorded on SR image plates, which were read using a GE Typhoon scanner and converted to units of photo-stimulated luminescence (PSL). This method allows for a relative comparison of signal brightness from each μ-flag targets.

Orthogonal to the TCS and edge-on to the Ag μ-flag target, the HERIE x-ray imaging diagnostic was used to measure the spatial profile of the emitted x-rays. A gold mask with alternating open regions was imaged by the HERIE at $\approx 20\times$ magnification. The time-integrated spatial extent of the x-ray emitting volume was assessed by measuring the width of the light-dark transition of the Au knife edges, differentiating to determine a line spread function, and from this calculating the modulation transfer function (MTF) of the system. The MTF quantifies the resolution of the imaging system, which is dominated by the x-ray source size in this configuration.

III. ANALYSIS

The spectral x-ray signal measured by the TCS is shown in Fig. 2. There are several features in the data that can be understood based on the x-ray generation mechanisms described previously. The measured emission from the bare and tamped (100 μm HDC backing) foils are nearly identical. This indicates that the plasma conditions are similar for the two targets, including the ionized charge states in the expanding plasma plume that is responsible for the shoulder of emission at higher energy than the Kα_1 peak. The intensity of the K$_\alpha$ radiation generated by the two targets is also very similar, indicating that the conversion efficiency is similar for a bare 10 μm Ag foil and one which was tamped on one side with HDC. Previous experiments using high-intensity pulses showed a significant reduction in hot electron refluxing efficiency when a thick (5 mm) Al backing was used [4]; this effect may be less pronounced for the thinner, non-conducting HDC tamper used in the present work.

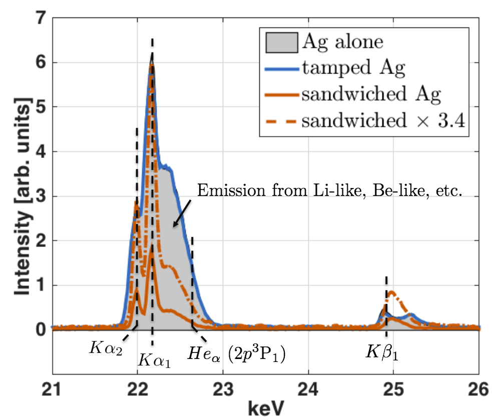

FIG. 2: Measured spectra from the TCS diagnostic. The free-standing Ag foil and one tamped with 100 μm of HDC produced nearly identical spectrum, shown by the shaded gray region and blue line, respectively. The sandwich target was lower in intensity (solid red), but when scaled up by 3.4 $\times$ (dashed red) is seen to have a significantly different spectrum.

In Fig. 2, the signal from the sandwiched target is shown relative to the other targets (solid red), and also scaled by 3.4 $\times$ (dashed red). The decrease in the $K\alpha$ signal in the sandwich target is likely due to a combination of factors, including a decreased hot electron population when the laser strikes HDC instead of Ag, the attenuation of some fraction of hot electrons in the laser-facing HDC, and a decrease in refluxing efficiency from the sandwich. When the signal is approximately normalized to match the $K\alpha$ peak from the bare Ag target (dashed red in Fig. 2), the effect of the thin HDC on the emission from higher charge states is evident. X-rays from the Li- and Be-like charge states are greatly reduced (though the distribution of charge states inferred from the shape of the shoulder is not significantly different). Finally, the ratio of K_β to K_α

in the sandwiched target is measured to be 0.14. For the targets where the Ag foil is directly irradiated, this ratio is less, ~0.03, indicating that there is bulk heating of the directly-illuminated Ag targets that serves to depopulate the M-shell and reduce the $n = 3 \rightarrow n = 1$ transition [5, 6].

The spatial coherence of each source was assessed by imaging a gold target with a set of open regions, producing an image with a set of edge transitions between full x-ray flux and nearly zero x-ray flux. For each x-ray source, 6 regions were sample to averaging out statistical photon noise and produce the edge spread function (ESF). Numerical differentiation of the ESF yielded the LSF, which was fitted by a function that was the sum of two Guassian curves: $f(x) = \sum_i^2 A_i \times \exp\left[\frac{(x-x_i)^2}{2\sigma_i^2}\right]$. This was seen to fully capture the shape of each LSF. A Fourier transform of the LSF led to the modulation transfer function, which is shown for each source in Fig. 3.

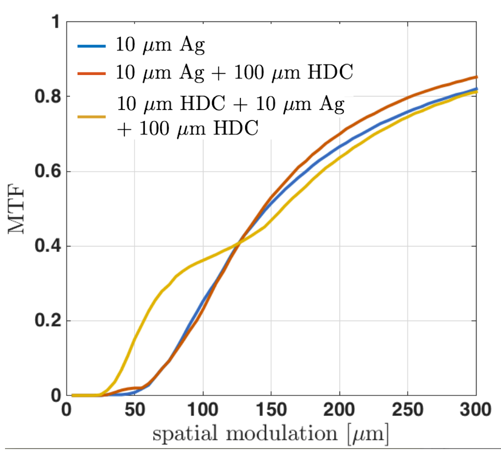

FIG. 3: The modulation transfer function measured from each of the μ-flag x-ray sources. A greater percentage of the x-ray flux in the sandwich target was generated from a narrow emitting volume, resulting in a more planar source.

The shape of the MTF curves reflect the relatively intensities of the Gaussian components used to fit the LSF. Each target tested produced a component of x-ray signal that was well-fit by a Gaussian with $\sigma \approx 30$ μm. Only the sandwiched target produced a significant second peak, which was narrower ($\sigma \approx 12$ μm) and higher in intensity (by $\approx$2.5 $\times$) than the broad peak. This strongly double-peaked structure in the LSF results in the inflection point seen near 140 μm in the MTF of the sandwich target. It is speculated that the thin HDC layer contains the plasma plume that expands from the heated Ag foil when it is directly irradiated, producing a narrower emission volume.

IV. CONCLUSIONS

Using a laser pulse on the order of one ns, the spectral content of high-energy (>17 keV) sources will necessarily include contributions from K shell transitions and from ionized states. In applications where the spectral content of the x-ray probe is important, laser-side tamping serves to narrow the K_α peaks and increase the ratio of K_α to He_α. In incoherent x-ray Thomson scattering experiments where the information about the plasma state is measured as a broadening of the initial x-ray spectrum, such a source may be a significant improvement. Additionally, the tamped target generated a greater fraction of its total emission from a more localized position, producing a slightly more planar x-ray source relative to direct laser irradiation of the Ag foil. Other experiments using a 1 ns laser to generate x-rays from high-Z (Nb) sources have demonstrated significantly higher resolution using a slit-projection geometry [7], and a future experiment combing slit projection with drive-side tamped foils may yield further improvement in spatial coherence and spectral content.

V. ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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